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A SUMMARY OF NASA/AIR FORCE FULL SCALE ENGINE RESEARCH PROGRAMS USING THE F100 ENGINE

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ABSTRACT

This paper summarizes a joint NASA/Air Force Full Scale Engine Research (FSER) program conducted with the F100 engine during the period 1974 through 1979. The program mechanism is described and the F100 test vehicles utilized are illustrated. Technology items which have been addressed in the areas of swirl augmentation, flutter phenomenon, advanced electronic control logic theory, strain gage technology and distortion sensitivity are identified and the associated test programs conducted at the NASA-Lewis Research Center are described.

Results presented show that the FSER approach, which utilizes existing state-of-the-art engine hardware to evaluate advanced technology concepts and problem areas, can contribute a significant data base for future system applications. Aerodynamic phenomenon previously not considered by current design systems have been identified and incorporated into current industry design tools.

INTRODUCTION

The Full Scale Engine Research (FSER) program at NASA's Lewis Research Center provides an economical means to strengthen the Technology base for future development of gas turbine engines. This cooperative program with the Air Force's Aero Propulsion Laboratory utilizes surplus engines of recent vintage as test beds for research. These engines are made available by the Air Force as they are retired from development or flight programs. The FSER program emphasizes technology advances rather than solution of hardware development problems. The objective is improved understanding of current problem areas, leading to the development of criteria and analytical techniques for design of future engines. This objective normally cannot be addressed in engine development programs, which must concentrate on meeting existing requirements of the aircraft systems. Current areas of investigation in the FSER program include fan and compressor flutter, inlet distortion effects, advanced augmentation concepts, and digital electronic controls design methodology.

Several of the FSER investigations during the 1974-1979 time period utilized the Pratt & Whitney F100 augmented turbofan engine and several future studies are planned with this engine. The F100, a high thrust-to-weight ratio engine representative of current technology, can be readily modified for research purposes because of its modular construction. The investigations accomplished and planned with the F100 engine are summarized in this paper in order that the engine community in general may have an awareness of the studies and the potentials of such research.

This paper presents information on a number of topics included in the four technology areas noted. Initial F100 FSER programs (1974-1976) were directed only toward basic aerodynamic research of a flutter problem which preproduction prototype F100 engines had encountered. In 1976 the FSER activity was expanded to include several advanced technology augmentation programs. In 1977 and 1978 the program was further expanded in scope to include electronic controls design technology and traditional evaluation of F100 engine stability from combined temperature and pressure distortion. Current and future programs are continuing the research efforts in all four areas of technology as well as smaller "piggy back" or spin off topics which have been investigated as part of the major research activities; Figure 1 illustrates the F100 FSER program scope.

GENERAL PROGRAM APPROACH AND WORKING CRITERIA

In the Full Scale Engine Research programs a thoroughly instrumented engine is installed in an altitude facility at the Lewis Research Center and tested at simulated altitude conditions. Program test requirements are identified from developmental engine experience as to where known problems occur or from advanced design studies provided by the Air Force or the Engine Manufacturer.

The actual engine instrumentation used, the hardware configuration utilized and the overall program ojbectives are jointly defined by the NASA, the Air Force Aeropropulsion Laboratory, and Pratt & Whitney Aircraft. In the aeromechanical programs, for example, the Air Force supplied a preproduction prototype YF100 engine to NASA to be used for flutter investigations. NASA collaborated with Pratt & Whitney Aircraft and the Air Force to design and install appropriate strain gages, pressure instrumentation and temperature instrumentation necessary to conduct a comprehensive flutter test program. Test plans were constructed to investigate the aeromechanical instability regions which P&WA had identified during the development phase of the engine.

All test activities included technical support from P&WA and spare engine hardware support from the Air Force to ensure operational problems were kept to a minimum. Data analysis and interpretation was conducted independently at NASA and P&WA using alternate approaches. Results, conclusions, and program reports were published through NASA technical memorandum and/or NASA Contractor Reports. Distribution of all resulting program reports are available to industry upon request to the USAF or NASA.

DESCRIPTION OF ENGINE AND INSTALLATION

The engine model used in the programs described in this paper is the F100-PW-100 twin spool, high thrust-to-weight ratio, afterburning turbofan engine. The low-pressure rotor has a three-stage fan driven by a two-stage, low-pressure turbine. The high pressure rotor has a 10-stage compressor driven by a two stage high pressure turbine through a shaft that is concentric and corotating with the fan shaft. The fan rotor is supported by three bearings and the rear compressor/turbine rotor is supported by two bearings. Air cooling is provided to the high pressure turbine blades and vanes. Variable vanes are located at the fan inlet, the compressor inlet and front three stages of the rear compressor. The engine design also includes a fully annular combustor with sixteen fuel nozzles, a mixed flow five segment augmentor with electric ignition and a lightweight balanced beam variable area convergent-divergent exhaust nozzle. A gearbox is mounted on the bottom of the engine to provide aircraft accessory drives. The various engine components are modular in construction, Figure 2, to provide ease of maintenance and interchangeability at the depot level.

The F100 engine is controlled by a combined gas generator and augmentor control. Its principal of operation is hydromechanical, using cams to provide schedules, and hydraulic servo systems for cam operation. An engine mounted digital computer provides supervisory trimming control over the hydromechanical control system to maintain optimized and safe gas generator operation.

The F100 engine is in the 25,000 lb thrust class with an overall fan and compressor total pressure ratio of 23 to 1. The ratio of fan airflow bypassed around the high pressure compressor to the airflow entering the compressor is nominally 0.7 to 1 at the sea level standard day conditions.

Engine test operations are conducted in any of four altitude chambers of the Propulsion System Laboratory at the Lewis Research Center. Figure 3 shows a typical engine F100 installation in a PSL chamber. A schematic drawing showing the engine installed in the test cell is presented in Figure 4.

I. F100 EXPERIMENTAL INVESTIGATIONS OF FLUTTER

As a result of modern emphasis on improved performance and lighter weight propulsion systems, flutter has emerged as an area of concern in the design of both military and commercial engines. Highly loaded, thin section elastic blades required for performance benefits provide favorable conditions for aeroelastic instability to occur. By definition, the flutter phenomenon involves a nonengine order integral response, negatively damped, which is caused by an interaction of aerodynamic forces and structural deformation.

Developmental problems encountered during several Air Force and Navy engine programs provided the Government impetus to develop a better understanding of the nature of flutter, the end product intent being to develop the necessary design system capability to avoid such problems in the next generation of engines. F100 stall flutter problems were identified in late 1972 and reported by Jeffers and Meece, Reference 1. Their investigations of that phenomenon formed the basis for initial F100 FSER program in early 1974.

The engine used in this program was a YF100 series I engine (serial No. FX 213-15) which had been retired from the F100 experimental development program. As reported by Lubomski, Reference 2, the engine first stage fan blades were susceptible to subsonic/transonic stall flutter in above shroud torsion at elevated inlet temperatures and pressures (i.e. at high Mach number flight conditions).

The engine was refurbished and prepared by P&WA with appropriate aerodynamic and strain gage instrumentation to map the flutter instability and identify associated frequencies and excitations within the system. The program was conducted in three phases:

Phase I simply provided the engine baseline performance data and developed the operational procedures and equipment necessary to conduct the test program.

Phase II added the aerodynamic and strain gage instrumentation reported in Reference 4 and illustrated in Figures 5 and 6.

Phase III added additional strain gage instrumentation.

During the course of flutter testing, which began in November 1975, the engine was run at several inlet conditions while attempts were made to induce the first-rotor flutter instability. In order to accomplish this task in a controlled method the engine fan operating point was driven toward the stall point along a constant speed operating line. Remotely controlled actuator systems on the engine fan inlet guide vanes and the engine exhaust nozzle were utilized for this purpose. To gain the necessary amount of back pressure required an exhaust nozzle plug was also used.

Steady state data were recorded before the beginning of each constant speed line excursion toward the stall region. High-speed digital and analog data were recorded during the excursion. Flutter onset was defined at a predetermined flutter stress level (based on P&WA's recommendation from fatigue life estimates of the various vibratory modes experimentally determined through shaker table testing of individual blades. Steady-state data was again recorded once flutter onset was determined. The speed line excursion was then reversed and the engine returned to a stable operating line point (Figure 7).

Using this procedure, flutter buckets were mapped for various combinations of inlet pressure and temperature, fan corrected speed, corrected flow and pressure ratio. Two major stall flutter regions were explored in this manner. The first region covered corrected first rotor speeds between 64 and 73% near the normal operating line at high inlet temperature and pressure. The second region covered included near surge pressure ratios at corrected fan speeds of 80 to 85% and low inlet temperature and pressure. Thirty-three data points in flutter were obtained using this procedure. In addition, a wide range of aerodynamic information was acquired from overall fan performance and from interstage pressure and temperature measurements which proved to be extremely useful in the analysis of the flutter data.

Experimental results and data format of the preliminary fan flutter investigations are described in detail in Reference 3. In this report the flutter is identified as predominantly above-shroud torsion of the first stage rotor blades. The vibratory frequencies are reported to have varied from 1067 to 1095 Hz for the flutter data acquired. The experimental apparatus used for the collection this data is described in References 4, 5, and 6. A documentation of the fan flutter regions investigated which illustrate the effects of inlet pressure and temperature of the location of the flutter boundaries on the fan operating map is presented in Reference 7.

FLUTTER DATA ANALYSIS

The characteristics of the F100 flutter phenomenon were later evaluated by independent researchers at NASA LeRC and under NASA Contract at P&WA. A summary of the characteristics of the aeroelastic instabilities identified in these programs and another engine manufacturer's engine test programs conducted at LeRC is discussed by Lubomski in Reference 2. The subsonic stall flutter response of the F100 rotor blades in flutter is described as varied, in which several frequencies are evident and one was predominant on most of the strain gages. Blade to blade variation in maximum displacement was apparent from both strain gage and light probe measurements, Reference 5. Response is described as initially occurring in small groups of blades upon penetrating the flutter boundary and then as the excursion into the flutter region progressed more of the blades would become active. Changing inlet pressures and temperature affected the rotor blade response, location of the flutter boundary (Figure 8) and the flutter frequency. Speed changes tend to affect the flutter frequency as well. Several hypotheses are presented by Lubomski to explain the system response to changes in inlet density condition or speed. Four additional types of flutter identified on a turbojet engine program are also addressed in Reference 2.

ANALYSIS USING A SEMI-EMPIRICAL TECHNIQUE

An existing P&WA semi-empirical technique for the prediction of airfoil subsonic stall flutter in gas turbine engines was also evaluated under contract to NASA as a technology spin off of the F100 FSER flutter program, Reference 8. Using a semi-empirical approach, airfoil stability for the first rotor YF100 engine was predicted by a cyclic energy method in which unsteady aerodynamic damping is calculated and a beam type vibratory motion model is used to predict the unsteady airfoil motion. Flutter occurs when the total system damping (aerodynamic plus mechanical) becomes less than zero. Experimental F100 flutter boundaries on a fan performance map were compared to those constructed from correlations of calculated aerodynamic damping. The semi-empirical system was determined to correctly predict changes in stability due to changes in fan speed, corrected flow, pressure ratio and total inlet pressure (for a given total inlet temperature and an assumed mechanical damping value). Correct predictions could not be made for changes in total inlet temperature nor could the effects of interblade phase angle be accurately predicted. Inaccuracies were attributed to deficiencies in <u>both</u> the semi-empirical unsteady aerodynamics model and the vibratory mode shape modeling approach. A total of fifteen combinations of fan inlet temperature and mechanical rotor speed were analyzed, Table 1, which were chosen as representative of the engine fan flutter operating conditions.

SYNTHESIZING BLADE FLUTTER PATTERNS

As part of the flutter data analysis activities, research was conducted at LeRC by Kurkov and Dicus, Reference 10, to develop alternate techniques for the detection of flutter and synthesis of the flutter wave patterns. Two approaches were evaluated, one utilizing the optical data described in Reference 5 and a second method by which construction of rotor vibratory patterns are made from aerodynamic-instrumentation. The optical data, which consisted of blade tip displacement measurements by photoelectric scanning methods, was digitized and reduced to relative vibratory amplitude and phase angles via spectral analysis with a Fast Fourier Transform (FFT) algorithm. Stationary mounted transducers and a high-response probe in the form of a miniature cantilevered beam probe were utilized to provide aerodynamic data which again was reduced via FFT methods. Resulting vibratory rotor patterns were generated for common data points and favorably compared to strain gage data analysis results as shown in Figure 9. The results show categorically that flutter can be detected and analyzed from high response pressure records as well as photoelectric scanning devices to detect blade displacement.

PLANNED F100 FLUTTER ACTIVITIES

Extensive analysis of the flutter data collected in the F100 FSER Program has identified areas of uncertainty where specific parametric investigations are needed to further understanding of the flutter phenomenon. With that purpose in mind, another F100 prototype fan blade has been chosen for investigating effects of mechanical damping changes, shroud location on the airfoil, blade tip thickness to root thickness ratio, temperature and system mode effects. Figure 10 illustrates the blade configuration which has been instrumented and will be used for additional flutter testing on an early production F100 engine S/N P680026 and will undergo analysis in 1980. The data from this planned test program will be useful in evaluating the hypothesis proposed by Lubomski, the results of Kurkov and the assumptions used in the derivation of the P&WA Semi-Empirical Flutter Prediction Technique. As a result, the original program guidelines of establishing a meaningful data base for developing design methodology to accurately predict airfoil instability prior to costly developmental testing may be fulfilled for the next generation engine program. This methodology also is currently being used in the design of a selective composite reinforced 1st stage fan blade for an advanced version of the F100 engine.

COMPOSITE INLAY FAN BLADES

The use of composite materials for flutter deterant by selective reinforcement of thin section airfoils was technically demonstrated by Detroit Diesel on the TF41 engine under Air Force contract, Reference 12. As a result of that program, the Air Force and NASA have collaborated to apply that technology to an advanced F100 blade design and eventually will demonstrate the blades in a F100 FSER program at LeRC.

Under contract to NASA, P&WA is currently using the combined results of the flutter programs described in this paper and the Air Force composite inlay technology to design a shroudless version of the advanced F100 shrouded 1st stage fan blade. Objectives of the existing program are to define the composite inlay geometry and fiber orientation required to remove the midspan shroud from the advanced F100 1st-stage fan blade. If successful, the benefits of such an approach would be identified by a projected increase in overall engine system performance of 1-1/2% or for the same level of performance a 22°F reduction in turbine temperature.

The current program will perform static and normal vibratory mode analysis on eight blades of all metal design and the same blades after the composite reinforcement material is installed into the airfoil. The blade testing will include the determination of the blade natural frequencies and mode shapes and a comparison made with the predicted design values generated in the preliminary design study. When this is accomplished the finite element models for the all-metal and composite inlay blades will be refined as required to reach agreement between analysis and test. The final effort in this program will be to recommend a design configuration for a set of engine quality blades which can be fabricated and tested in the NASA FSER engine. Figure 11 represents an 8-ply composite reinforcement configuration which resulted from the previous Air Force program. FSER test demonstration of the advanced F100 blade is anticipated to take place in 1981.

AIRFOIL CHOKE FLUTTER INVESTIGATION

In addition to subsonic stall flutter, previously discussed, airfoil choke flutter poses a serious problem for gas turbine engine design because no analytical model exists for the calculation of the airfoil unsteady aerodynamic environment. The complex nature of this environment has so far resisted rigorous mathematical formulation, but an effort to develop a simplified model is currently proceeding at P&WA under NASA contract. The simplified model is based on a channel-flow approach originally used by NACA-NASA to analyze inlet diffusers of turbojet and ramjet engines. In the model, shock dynamics are considered to have strong influence in the unsteady lift and moment on a cascade of airfoils oscillating in comprehensible choke flow.

When complete in 1980, the model will be evaluated using available data from FSER flutter programs or available data from the engine manufacturers developmental experience. The results will be published in a NASA contractors report.

STRAIN GAGE RELIABILITY

Early in the F100 FSER Flutter test programs, the need for increased reliability and full life strain gage instrumentation became apparent. Initial programs used strain gaging techniques and applications which, at the time, were representative of the state-of-the-art, but wholly inadequate to withstand the rigors of elevated inlet temperatures and erosive facility air delivery systems. As a result, a 25-month program was initiated to determine the reliability of various strain gage systems when applied to rotating compressor blades in aircraft gas turbine engines. The intent of the program was to identify specific systems offering the highest reliability. The work, conducted under NASA Contract, included a survey of current strain gage technology (Table 2), installation of seven promising systems on an early production F100 fan module, testing of the fan module for 68 hours in a F100 FSER simulated altitude program and analysis of the results. As a result of the program, strain gage system materials, application technique and coatings were identified and are discussed in Reference 9. A comparison of the strain gage failure rate for this program versus the F100 flutter test program is shown on Figure 12. The initial high failure rate in the flutter programs is now assumed to be due to poor blade to disk jump formations and later failures attributed to poor erosion resistance in the early program systems. The strain gage research program demonstrated the need for a comprehensive engineering evaluation of the strain gage application prior to use in engine test programs; Reference 9 should serve to provide valuable guidelines for any strain gage application with turbomachinery hardware.

II. F100 EXPERIMENTAL INVESTIGATIONS IN AUGMENTATION TECHNOLOGY

In the military application of high thrust-to-weight ratio turbofan engines periodic large increments of thrust are often required to fulfill mission requirements such as takeoff, acceleration and maneuvering. The thrust increment is generated through the use of a thrust augmentation system called an augmentor or afterburner. Afterburning systems have been in use in turbojet engines for more than 20 years using basic flameholding technol-ogy depicted in Figure 13. Since the application of afterburners to turbofan engines, stability problems have been common from the requirement to mix core and fan duct streams, distribute the fuel and vaporize it to provide a uniform fuel air mixture within the combustion volume and with high combustion efficiency at temperatures near stoichiometric.

Existing turbofan augmentor systems use a flameholder to create a low velocity recirculating air region that allows flameholding and propagation within the high velocity augmentor air stream. In the flight regime on an altitude Mach No. plot commonly referred to as the upper left hand corner (UHLC), fan stream airflow is cold (<300°F), the pressure is low (<12 psia) and jet fuel vaporization characteristics are poor. The result is nonuniform augmentor fuel air mixtures which create ignition and combustion problems, rumble, blowouts and mislights.

The Air Force, recognizing the difficulties associated with optimization of afterburning turbofan system, has sponsored extensive research of the problem which has included rig testing as well as analytical modeling of the system.

Basic research has also been underway within private industry and at NASA to improve basic turbofan augmentor combustion characteristics. The research at P&WA has been directed toward the concept of swirling flow augmentors. In this application a strong centrifugal field is generated by swirling the flow with vanes at the augmentor inlet. In operation, hot flame pilot gases either from a pilot flameholder or a fan stream annular pilot combustor are displaced towards the center of swirl by buoyant forces, producing subsequent combustion products and a continuous ignition source across the stream. Several full scale swirl augmentor rigs have been designed and tested at P&WA, one of which is shown in Figure 14, with promising results to reduce stability problems in the ULHC.

NASA LeRC and the Air Force, in recognizing the generic problems associated with ULHC turbofan augmentor operation, incorporated additional test activities into the F100 FSER program which would evaluate the Air Force funded modeling results on existing augmentor systems and evaluate the swirling flow augmentor concepts pursued by P&WA.

The FSER augmentor programs were initiated in 1976 and consisted of sea level baseline testing at P&WA followed by simulated altitude evaluation at LeRC. Testing was conducted on the F100 Bill-of-Material augmentor, modifications of the Bill-of-Material system and two swirl type augmentor configurations. In addition to augmentor hardware considerations, attempts were made to isolate sources of augmentor problems by employing fuel supply tailoring with stand mounted fuel supply systems and sophisticated controls approaches with a Digital Electronic Breadboard Engine fuel control.

F100 RUMBLE MODEL EVALUATION

Air Force sponsored combustion technology programs have included development of modeling techniques of combustion systems to provide a design tool for future applications. P&WA developed, under contract to the Air Force, a prediction model of the F100 engine/augmentor for rumble and combustion instabilities. Predictions generated by this model were evaluated by NASA in F100 FSER testing during the Spring of 1977. Augmentor efficiency and stability data were collected in ULHC operation and supersonic areas of the F100 flight envelope. The results of this testing, reported by Russell and Brant in Reference 12, provided the necessary information to the Air Force modeling program for refinement and development of that design tool.

Included in this program was identification of the augmentor control scheduling effects, i.e., a remotely controlled augmentor flowcart was used to optimize the individual augmentor segment flows and results compared to BOM engine results. In addition, modifications were made to the sprayrings and flameholder to change fuel vaporization/distribution characteristics and calibrate the sensitivities of the various analytical parameters which make up the Air Force model's architecture. Those altitude test results from the swirl augmentor tests, later conducted at LeRC, were also fed into the model to address the effects of the swirling flow field.

One important aspect of the augmentor testing which should be noted was the use of a gas sampling system developed at LeRC to determine chemical system efficiency. These results were compared to efficiency levels calculated from the engine system thrust measurements made in the PSL facility tests. This reduced the relatively large degree of uncertainty normally associated with calculated augmentation combustion efficiencies.

SWIRL AUGMENTOR TEST PROGRAMS

Two configurations of swirl augmentors have been tested at LeRC as part of the F100 FSER programs. These two schemes (Figure 15) represent technology which is applicable to both near-term and far-term engine system configurations. The full swirl augmentor, projected to be the superior configuration when fully developed for far-term applications, is the more complex system of the two tested. It is expected to provide superior UHLC transient capability, cruise TSFC benefits and significant side benefits such as reduced infra-red (non-augmented) signature plume irradiation as well as reduced idle engine thrust levels which the airframe industry desires. This concept can also be extended to short length augmentor and main burner applications.

The full swirl augmentor rig configuration tested in the FSER program consisted of adjustable fan stream and core stream swirl vanes, movable sprayrings of a variable area pintle design, a fan stream pilot combustion chamber and a remotely operated flow cart augmentor fuel system. A BOM engine augmentor fuel system was also used to investigate augmentor transient capabilities. A BOM F100 nozzle was used for all testing.

The augmentor test program at LeRC, results achieved and development efforts which led to the construction of the FSER rig test are described in detail by W. Egan in Reference 11. Testing at LeRC was initiated in September 1977 after sea level demonstration of the concept had been conducted at P&WA's Florida test facilities. Two build configurations were tested. Results of the build 1 tests were encouraging although the maximum altitude attained was 35,000 ft at 0.8 Mn where the fan stream pilot blowout limit was reached. To achieve additional altitude capability a redesigned and rig documented co-swirl pilot, was installed. The co-swirl pilot configuration was shown to have wider light and flammability limits; however, before a large amount of data could be collected nozzle hardware damage terminated the test program.

Follow-on efforts since that period have included additional design modifications of the pilot and sprayrings. A successful sea level demonstration of the configuration was completed and another altitude test program is planned at LeRC in August 1979 to complete the technology evaluation of this concept.

PARTIAL SWIRL AUGMENTOR TESTING

The second swirl augmentor configuration tested in the F100 FSER program consisted of an afterburner configuration which swirls only core stream airflow to generate a strong centrifugal flow field for flamespreading. This approach utilizes the basic F100 augmentor with the following modifications, Figure 15.

- o The Turbine Exhaust Case straightening vanes were altered to retain residual low pressure turbine swirl of approximately 20° at the afterburner inlet.
- o The inner core gutters of the F100 flameholder were removed.

Sea level testing of the configuration was conducted to determine the nonafterburning thrust effects from the retention of low turbine swirl. It was determined the reduced pressure loss achieved by removal of the flameholder core gutters offsets the thrust loss due to residual swirl at the exhaust nozzle thrust. Augmented performance and combustion efficiency values for the F100 BOM and partial swirl augmentor configurations were comparable.

Altitude testing was performed at LeRC in late 1978 in which a breadboard Digital Electronic Engine Control was used to optimize the augmentor fuel/air schedules peculiar to the swirl flow augmentor and perform snap transients. Altitude performance data was obtained at subsonic and supersonic conditions, up to 1.6 Mach Number. Snap transient capability was demonstrated above 50,000 ft at 0.6 and 0.8 Mach Numbers. In addition, rumble combustion characteristics were documented which showed a 10% improvement in fuel/air ratio capability over the BOM F100 configuration. The partial swirl augmentor program test results are discussed in Reference 13.

Currently the engine breadboard control system has been removed and testing continues with the F100 BOM control. When complete, a baseline F100 augmentor calibration will be run on the same engine. At the conclusion of this program, the benefits achieved with each of the hardware and control changes made will be identified. A possible adaptation of this concept to the current production F100 engine has been proposed to the Air Force and is under consideration.

III. DISTORTION AND STABILITY TECHNOLOGY PROGRAMS

In the past NASA-LeRC and P&WA have collaborated in the application of a P&WA circumferential distortion model to full-scale turbofan engines, results of that work are detailed in References 17 and 18. Follow-on activities included modification of that distortion model to include a variable vane geometry capability and applied specifically to the F100 engine, Reference 19. In order to demonstrate the capability of the model to predict engine response to both individual pressure and temperature distortions and combined pressure and temperature distortions, a program was initiated under NASA contract to P&WA.

In this program, the F100 distortion model was used to analytically predict engine system response for various levels of inlet pressure and temperature distortion. The analytical results achieved are described in Reference 20.

Five circumferential pressures and four temperature distortions were evaluated individually. The predicted engine response parameters were component rematch due to distortion, stall line degradation of the limiting component, attenuation/generation of distortion across the core flow stream, and the distortion path through the compression system.

The feasibility of predicting the combined effects of inlet pressure and temperature distortions on stability by using the uncoupled distortion effects was addressed for nine combinations of engine conditions and distortions. An engine stability audit on the current production configuration F100 engine S/N XD11 was conducted to evaluate the analytical results achieved.

Results described in Reference 20 showed the pressure distortion predictions agree with F100 experience. The fan was relatively insensitive to temperature distortion and very little temperature attenuation was seen through the fan. The model was found to be a viable development tool, however, more generalization is needed before it can be applied as a design tool.

Future testing on the F100 engine S/N XD11 is planned as part of the F100 FSER activities. In that program, moderate (15%) to high (30%) levels of distortion will be subjected on the F100 engine. P&WA F100 distortion factors, as well as classical techniques and newly developing industry standards (SAE-16) can be determined. Engine measured sensitivity will be compared with the predicted sensitivities and engine system effects, i.e, bypass ratio changes can be determined. Additional modeling work is also planned to provide the necessary refinements required to utilize this tool more effectively for development purposes.

IV. ADVANCED ELECTRONIC CONTROLS PROGRAMS

During recent years aircraft engines have become complex machines involving the use of variable geometry stators in the fans and compressors, variable area nozzles and performance trimming computers. The next generation engines may impose additional requirements such as variable area turbine stators, variable turbine cooling air flow, variable area combustor and complex operating cycles for performance and/or environmental concerns. Classical control design techniques, which involve individual parameter loop control, have worked well for the older, simpler engines. However, such techniques are cumbersome and time consuming when applied to the type engines envisioned for future system applications. As a result, activity has been underway within the aerospace industry to apply modern control theory and advanced electronics components for optimization of engine control technology.

Several areas of interest have been pursued by NASA in the F100 FSER programs which relate to future control technology. These programs have included the development and use of real time, hybrid computer simulations, the demonstration of F100 engine control using linear quadratic regulator theory and application of Full Authority Digital Engine Electronic Control systems to improve engine control system operation.

Current programs involve the simulated altitude demonstration of a NAVY advanced electronic control system known as FADEC. Future programs planned by NASA involve simulated altitude and F-15 flight tests of an Integrated Propulsion Airframe Control System (IPAC) which will utilize a more advanced version of the Navy FADEC control.

APPLICATION OF REAL-TIME ENGINE SIMULATIONS TO THE DEVELOPMENT OF PROPULSION SYSTEM CONTROLS

Work conducted at NASA LeRC by Szuch, Reference 14, provides a means of analyzing the behavior and interactions of complex engine systems prior to full-scale engine testing. The development of controls for aircraft propulsion systems depends on the ability of the control engineer to accurately predict the performance of the aircraft, the engine, and their associated controls. In addition, simulations also serve as aids in the solution of problems that occur after the engine system development is complete. Reference 14 summarized the various simulation techniques and models available and currently in use. Major topics addressed include Real Time Engine Simulation using the Hybrid computer (digital and analog), bivariant function generation of fan and compressor maps, transient and steady-state operation, digital control development, sensor fail operational control development, real time engine simulation of the F100 engines and development of multivariable controls.

Air Force and NASA funded programs, supported by P&WA in the area of multivariable controls development, later utilized the techniques described by Szuch to develop a multivariable control system evaluated at LeRC in the F100 FSER program.

MULTIVARIABLE CONTROLS EVALUATION

Under contract to the Air Force, Systems Control, Inc. (SCI) with the support of P&WA applied linear quadratic regulator (LQR) theory to the F100 Controls application, described in Reference 15. LQR methods address the control of small perturbations about specified operating points and on various trajectories between the operating points. The actual engine controller program is a modularized design, functionally containing reference schedules, transition logic, integral control logic, gain scheduling logic, LQR gains and sensor compensation. The F100 FSER Multivariable Controls Program was intended to demonstrate the application of linear quadratic regulator theory to the design of a control system, which would be used to operate an advanced state-of-the-art turbofan engine throughout its operating range.

The MVC program was structured to obtain Bill-of-Material control engine performance over the F100 flight envelope points shown in Table 3 and were rerun on the same engine, a current production F100(3) engine S/N XD11, with the MVC. All of the test points were simulated on the LeRC hybrid computer prior to testing as described in Reference 14. Both steady state and transient testing was accomplished for MVC and Bill-of-Material controls configurations.

Testing included 186 hours of total run time in which 53 hours were completed with the MVC control. Stable operation at all flight conditions was demonstrated. The control design and evaluation points were selected to fully describe the engine operational flight envelope, with emphasis on regions of extreme conditions of pressure, temperature and control system limitations. The F100 Multivariable Control Logic is illustrated in Figure 16.

The transition control and protection limits worked well, as did gains scheduled as a matrix function of engine power and flight condition. Test results, however, showed the integral portion of the control mode tended to be slow. Excessive speed undershoot on deceleration and some match point offsets during augmentation was noted. These items can be corrected with additional control development.

As a result of this program, new ground has been broken with the application of LQR design procedures to jet engine control. The control algorithm is of conventional structure and, with the exception of the estimator techniques, can be applied to advanced engine designs where the increasing number of variable elements must be controlled and the related interactions will demand a more sophisticated approach to the control logic design. The algorithms also can be conveniently used for initial control development or preliminary design activity.

DEMONSTRATION OF A FULL AUTHORITY DIGITAL ELECTRONIC CONTROL SYSTEM

Under contract to the Navy, P&WA and the Hamilton Standard Corporation have designed, fabricated, and demonstrated in sea level testing on a F401 engine an engine mounted Full Authority Digital Electronic Control System (FADEC). The FADEC unit utilizes electronic circuit technology expected to be available for production type incorporation in a 1980 design time frame. This control system provides all the sensing, computation and signal conditioning functions which would be required for an advanced technology demonstrator engine. The system as described in Reference 16, features use of redundancy in sensing, electronic computation, and command circuit paths along with parameter synthesis and self-test techniques to cost-effectively provide fail operational gas generator backup control capability.

As follow-on to the successful sea level demonstration testing, NASA, by request of the Navy, has included an altitude evaluation of the FADEC control system as part of the FSER technology programs.

The FADEC demonstrator control consists of an engine-mounted, flight-weight prototype primary control and an off-engine breadboard secondary backup control console (Figure 16). In the engine system, these controls interface with fuel handling and geometry actuation hardware developed for use with an F100 Digital Electronic Engine Control. The altitude test program will evaluate the FADEC control performance and check the response of the various control loops. The altitude and Mach number conditions selected for these tests are shown in Table 4. Testing is underway and scheduled for completion by July 1979.

Although this program uses the F401 engine, it is mentioned here to provide continuity to the overall F100 FSER programs. The P&WA F401 engine is, in fact, very similar to the F100, in that they utilize a common core and a similar BOM control system. The F401 low spool, however, is sized to provide approximately 15% more airflow than the F100.

Future planned NASA technology programs in Integrated Propulsion Airframe Controls will use the FADEC control, i.e., an updated version, for basic control development, demonstration and technology investigations. That program will include simulated altitude testing at LeRC as well as comprehensive flight testing in one of the NASA F-15 aircraft.

CONCLUDING REMARKS

A brief overview of the past and current technology programs of the joint Air Force and NASA F100 FSER programs has been presented.

Although the programs which have been discussed are directed specifically toward the use of the F100 engine, it has been shown that technology contributions made and documented in these efforts create a data base applicable to industry's needs in general. The FSER program approach serves to illustrate that full scale engine evaluation of concepts and problem areas contribute to the general solution and basic understanding required for future design efforts. Results indicate that using current engines for the early comprehensive testing of new technology hardware has been found to provide a sound basis of evaluating the technology prior to commitment to costly and time consuming development activities.

ACKNOWLEDGEMENTS

The author's wish to thank Pratt & Whitney Aircraft Group of United Technologies Corporation, the NASA-Lewis Research Center and the Air Force Aeropropulsion Laboratory for permission to present this paper. Also, apologies are expressed to those individuals whose research efforts have been unintentionally neglected in the relatively brief overview of such a broad technical effort.

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TABLE 1. COMBINATIONS OF FAN SPEED AND METAL TEMPERATURE ANALYZED TO DETERMINE VIBRATORY CHARACTERISTICS

Combination Number	Fan Rotor Speed (%)	Fan Inlet Temperature		Mechanical Rotor Speed (rpm)
		(°C)	(°F)	
1	73.3	171	340	8781
2	70.2	171	340	8410
3	67.1	171	340	8040
4	64.4	171	340	7710
5	63.7	171	340	7630
6	70.0	149	300	8170
7	67.2	149	300	7850
8	66.9	149	300	7810
9	80.9	135	275	9290
10	74.4	135	275	8540
11	72.8	135	275	8360
12	70.3	135	275	8070
13	69.7	135	275	8000
14	64.4	135	275	7400
15	82.2	27	80	8090

TABLE 2. STRAIN GAGE SYSTEM COMPONENTS RANKED IN ORDER OF PERFORMANCE FOR F100 FAN APPLICATIONS

Surface Preparation

1. Grit blasting - #120 grit Al_2O_3

Bond Coating

1. Metco 450

Precoating

1. Rokide H (or HT) rod
2. Plasmalloy 331-M powder
3. Rokide S rod
4. SermeTel P-1 ceramic cement

Gage Wire

1. Nichrome V
2. Evanohm S - Karma
3. Platinum-Tungsten

Gage Size

0.79 cm x 0.24 cm
BLH HT-1212-2A - 0.32 cm x 0.16 cm
BLH HT-1212-5A - 0.79 cm x 0.24 cm

Attachment Coating and Overcoat

1. Rokide H (or HT) rod*
2. Plasmalloy 331-M powder*
3. Rokide S rod*
4. SermeTel P-1 ceramic cement
5. Bean H Cement

Leadwire

1. Chromel P (35 gage)
2. Platinum - 10 percent Nickel
   (36 gage with BLH HT-1212-5A strain gage)
   (40 gage with BLH HT-1212-2A strain gage)
3. Nichrome V (36 gage)

TABLE 2. STRAIN GAGE SYSTEM COMPONENTS RANKED IN ORDER OF PERFORMANCE FOR F100 FAN APPLICATIONS (Continued)

Blade-to-Disk Jump (First Stage)

1. Stranded nickel-plated copper - 32 gage - Kapton/Teflon insulation
2. Chromel/Alumel - 23 gage duplex - Fiberglas/Asbestos Insulation

Blade-to-Disk Jump (Third Stage)

1. Chromel/Alumel - 28 gage duplex - Fiberglass/Asbestos Insulation
2. Chromel P (35 gage)
3. Chromel/Alumel 34-gage, mineral-insulated, metal-sheathed wire

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*In composite installations, a ceramic cement such as Bean H is also used in the gage attachment process. The cement is used as a finish coat in the precoat and as an attachment coat for the gage and leads prior to application of an overcoat.

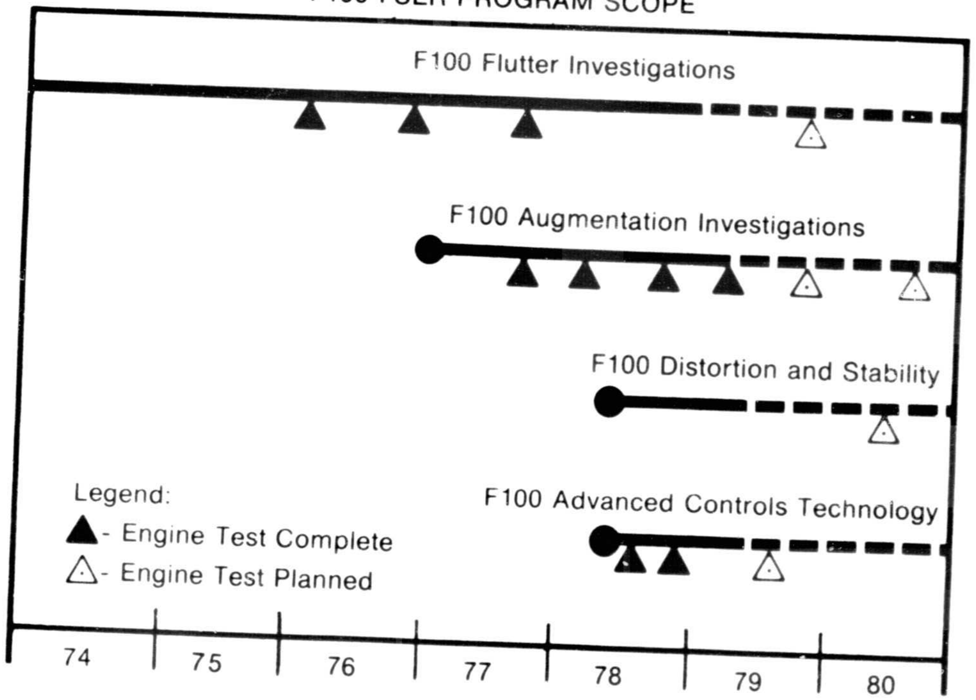
TABLE 3. SELECTED FLIGHT TEST POINTS

Point	Mach No.	Altitude [ft(Thousands)]	P_{t2} (atm)	T_{t2} (°R)	Criterion	Linear Model Points	SCI Design Evaluation Points	NASA Hybrid Test Points	NASA Engine Test Points
a	0	0	1.00	519	Basic Design Point	X	X	X	
b	0.9	10	1.16	562	Basic Design Point	X	X	X	X
c	0.3	20	0.49	456	Low Mn, Low Altitude	X			
d	0.6	10	0.88	519	NASA Test Point	X		X	X
e	0.6	30	0.38	442	Low Mn, Medium Altitude	X			
f	1.2	0	2.40	668	P_b Limit Point	X	X	X	
g	2.2	40	1.79	768	High Mn, Medium Altitude	X		X	
h	0.9	45	0.25	454	Low Mn, Medium Altitude	X		X	X
j	0.9	65	0.10	454	Low P_{t2}	X		X	X
k	2.5	65	0.84	876	High Mn	X		X	
l	0.9	30	0.50	479	Basic Design Point	X	X	X	X
m	1.8	75	2.05	652	High Altitude	X		X	
n	1.8	20	2.50	737	High Dynamic Pressure	X		X	
p	1.8	40	1.01	643	Low Supersonic Point	X			
q	2.15	58.5	0.69	750	NASA Test Point	X		X	
r	1.2	10	1.65	622	NASA Test Point			X	X
s	1.6	21	1.80	671	High Dynamic Pressure				X
t	1.9	32	1.70	697	High Mn, Medium Altitude				X
u	1.8	58	0.43	643	High Altitude				X
v	2.1	55	0.76	734	High Mn, Medium Altitude				X

TABLE 4. PROPOSED FADEC ALTITUDE F401 ENGINE TEST CONDITIONS

Point	Altitude (ft)	Mach No.	Comment
0	7,000	0.3	Functional Checkout
1	20,000	0.8	Probable Starting Point
2	10,000	0.9	
3	40,000	0.6	
4	50,000	1.6	
5	35,000	1.4	
6	35,000	0.8	
7	45,000	1.3	Optional Point
8	35,000	1.1	Optional Point

FIGURE 1
F100 FSER PROGRAM SCOPE



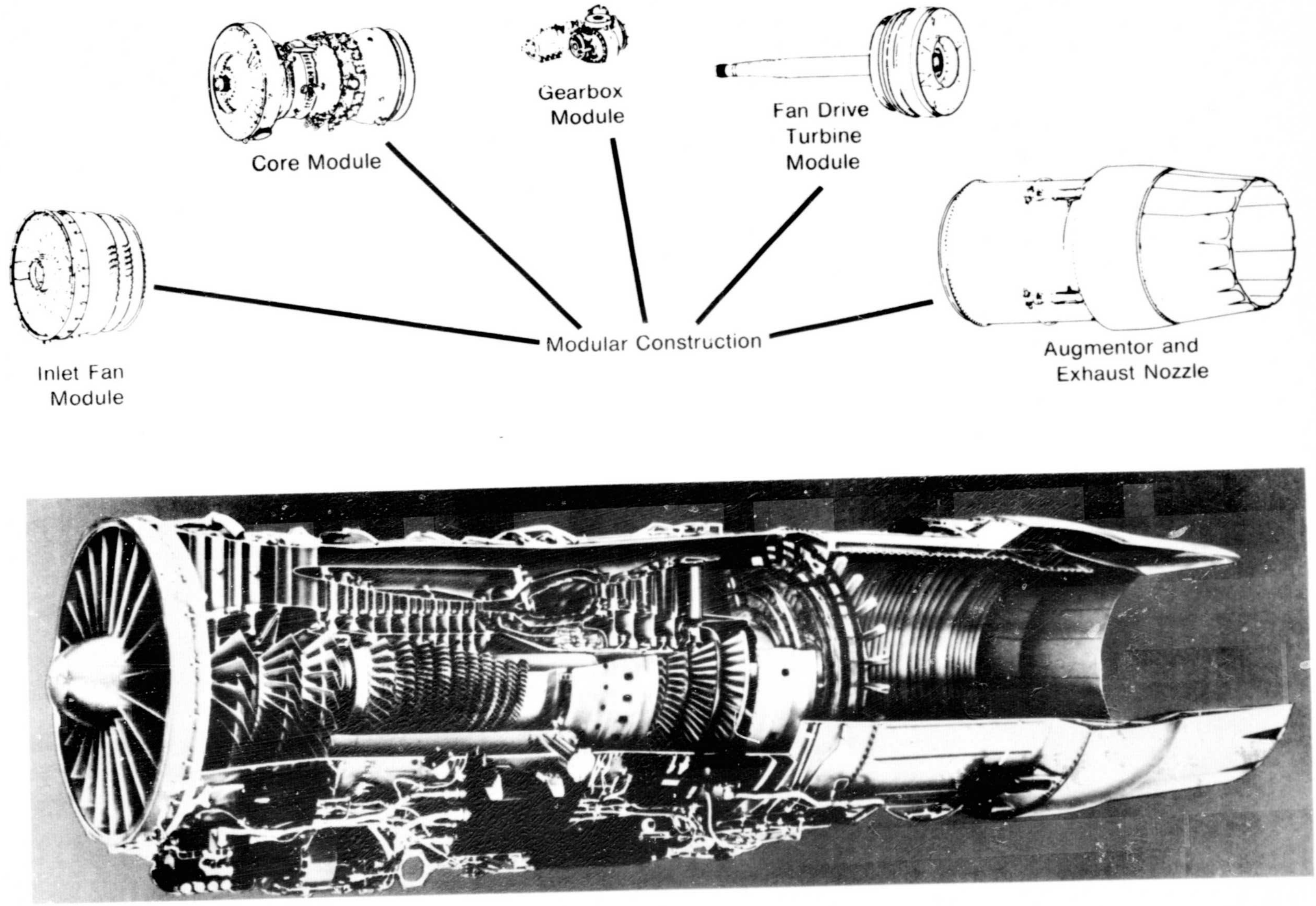
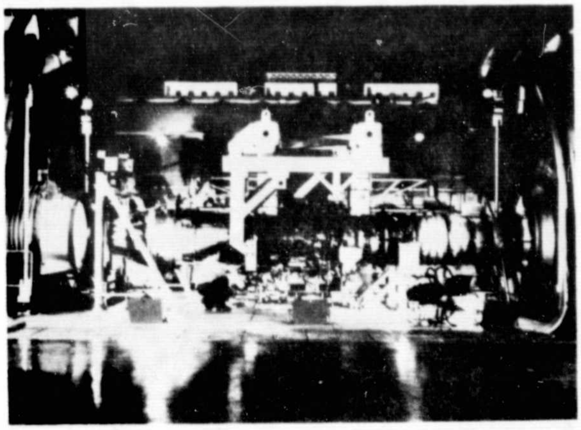
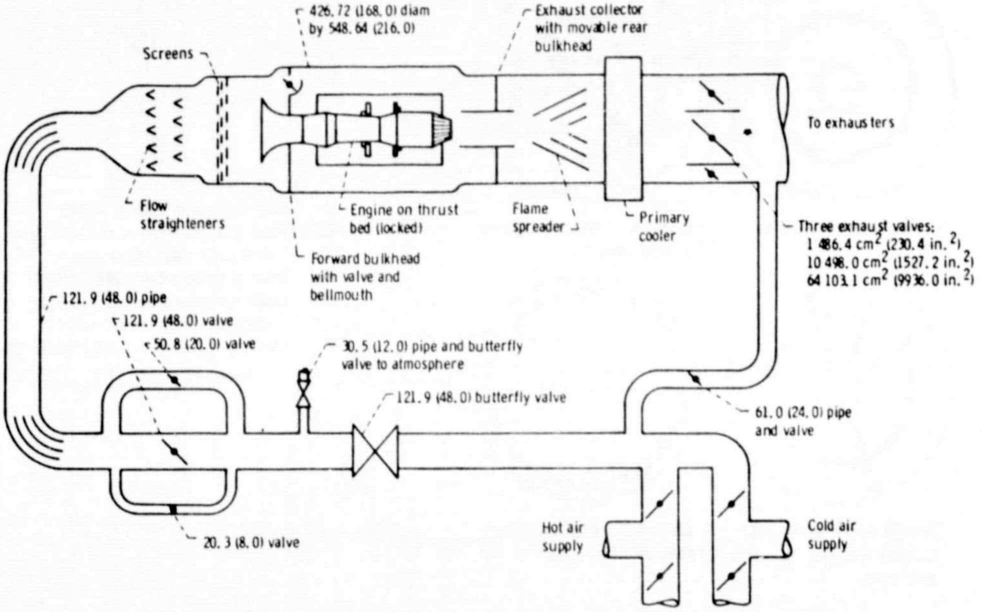


Figure 2. F100-PW-100 Turbofan Engine

FIGURE 3

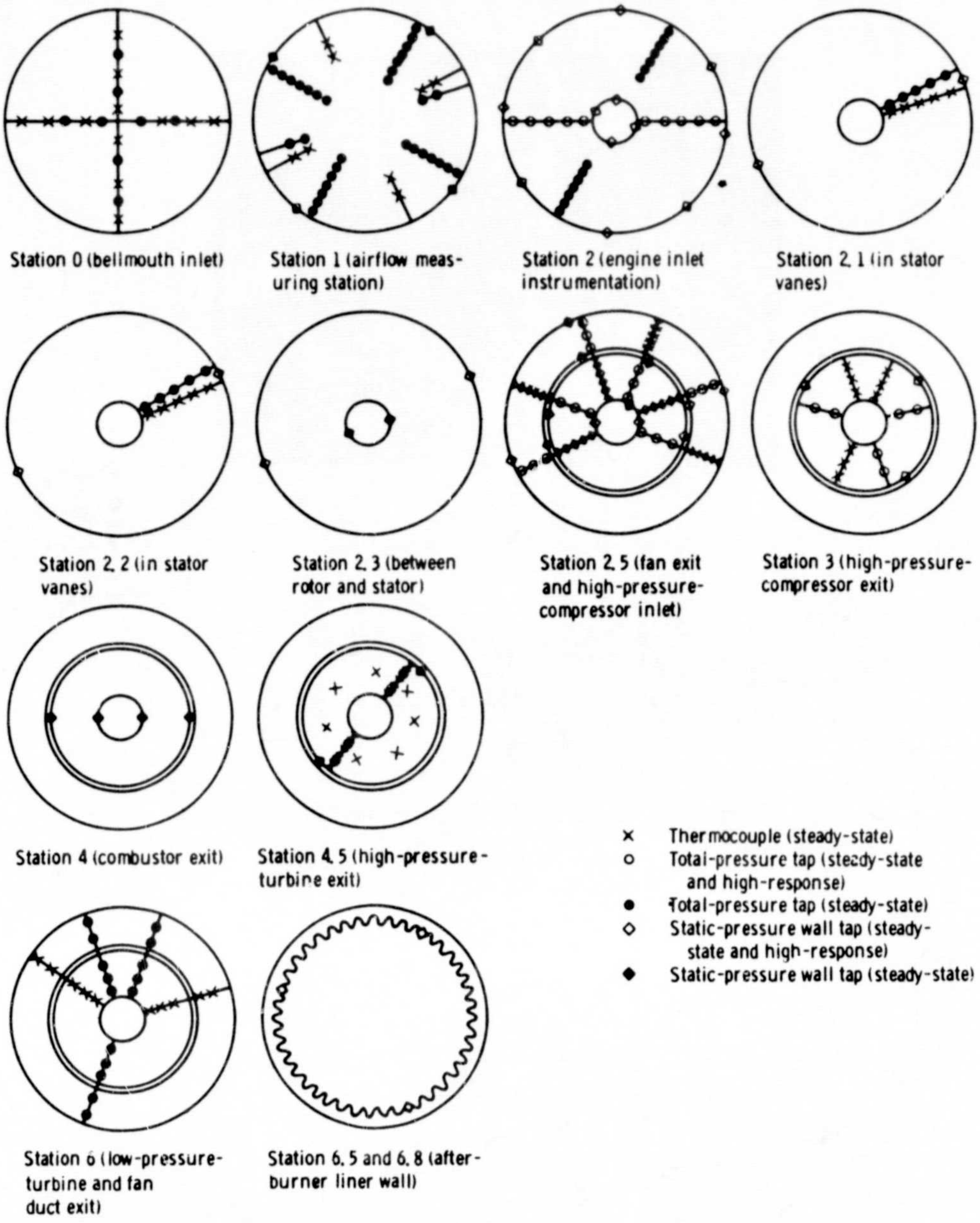
F100 ENGINE INSTALLATION IN PSL FACILITY





Note: Drawing not to scale. Dimensions are nominal in cm (in.) except as noted.

Figure 4. Schematic Diagram of the Propulsion Systems Laboratory Cell


Station 0 (bellmouth inlet)

Station 1 (airflow measuring station)

Station 2 (engine inlet instrumentation)

Station 2.1 (in stator vanes)

Station 2.2 (in stator vanes)

Station 2.3 (between rotor and stator)

Station 2.5 (fan exit and high-pressure-compressor inlet)

Station 3 (high-pressure-compressor exit)

Station 4 (combustor exit)

Station 4.5 (high-pressure-turbine exit)

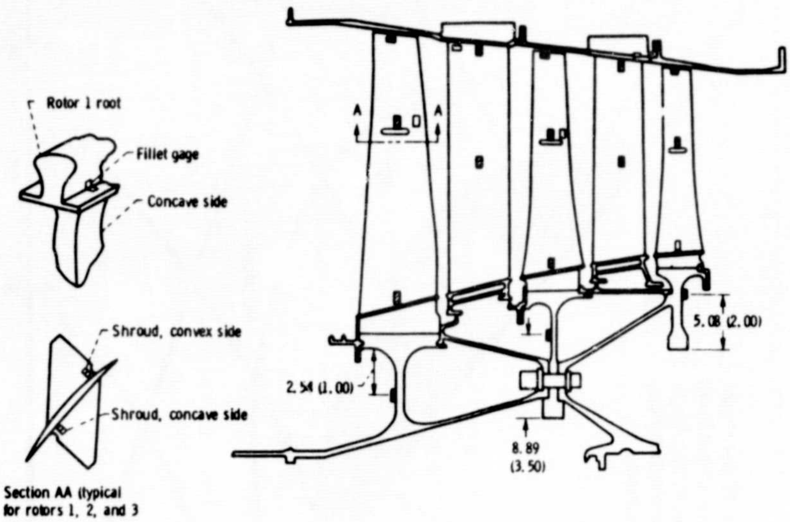
Station 6 (low-pressure-turbine and fan duct exit)

Station 6.5 and 6.8 (afterburner liner wall)

Figure 5. Schematic of aerodynamic instrumentation locations at each measuring station (viewed looking upstream)

	Strain-gage grid size	Strain-gage location
▭	0.7938 (0.3125) by 0.2381 (0.0938)	Airfoil, concave surface
▨	0.7938 (0.3125) by 0.2381 (0.0938)	Airfoil, convex surface
⊠	0.7938 (0.3125) by 0.2381 (0.0938)	Web, disk
◫	0.3178 (0.1250) by 0.1568 (0.0625)	Shroud or fillet (fillet rotor 1 only)

ASMT	Above shroud, maximum thickness
ASTE	Above shroud, trailing edge
SHRD CX	Shroud, convex side
SHRD CC	Shroud, concave side
RMT	Root, maximum thickness
D-web	Web, disk
ODLE	Outside diameter, leading edge
ODTE	Outside diameter, trailing edge
ODMT	Outside diameter, maximum thickness
MSMT	Midspan, maximum thickness

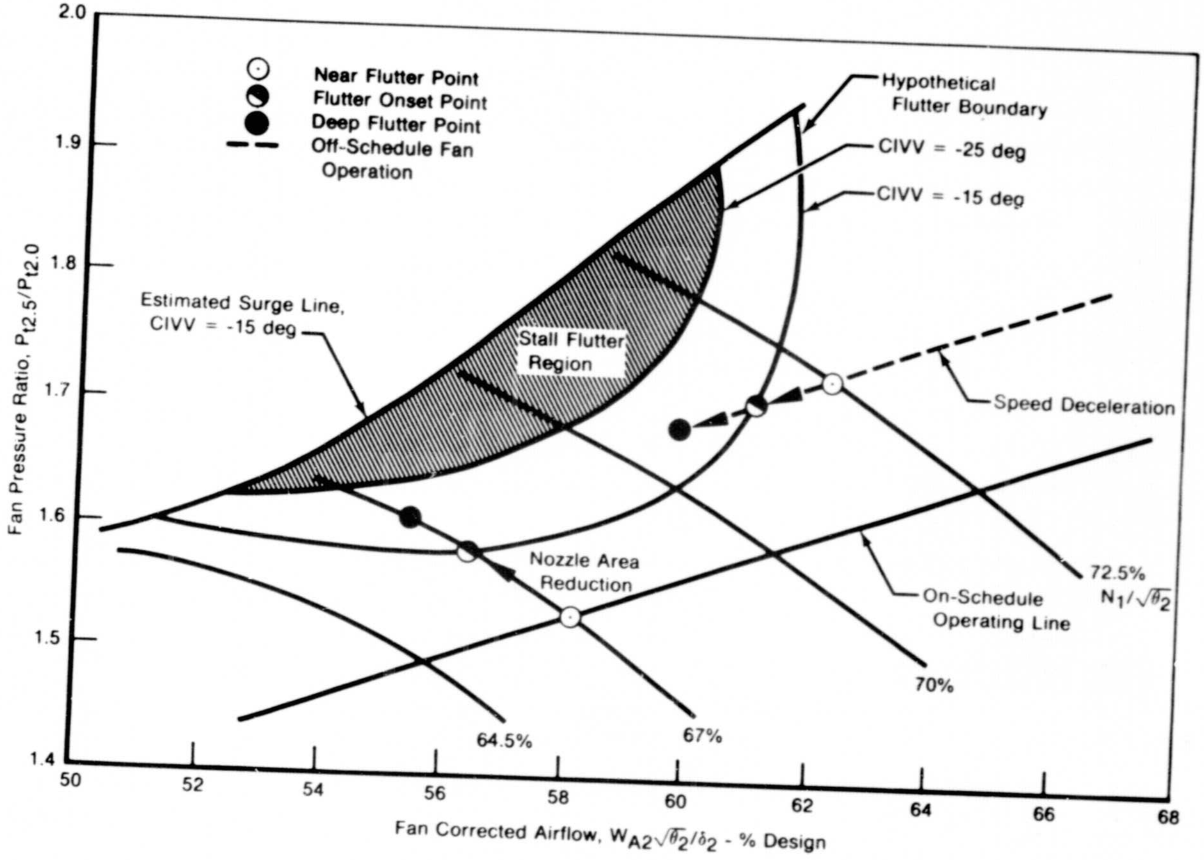


(a) Overall fan strain-gage locations.

(Dimensions are nominal values. Linear dimensions in cm (in.). Angles are clockwise from top dead center, looking upstream. Slot numbers are clockwise from top dead center looking upstream (slot 1 is top dead center). Drawings not to scale.)

Figure 6. Stuctural dynamic instrumentation

FIGURE 7
DECELERATIONS, NOZZLE AREA REDUCTIONS, AND CIVV SETTING CHANGES WERE EMPLOYED TO PROBE THE STALL FLUTTER DESIGN



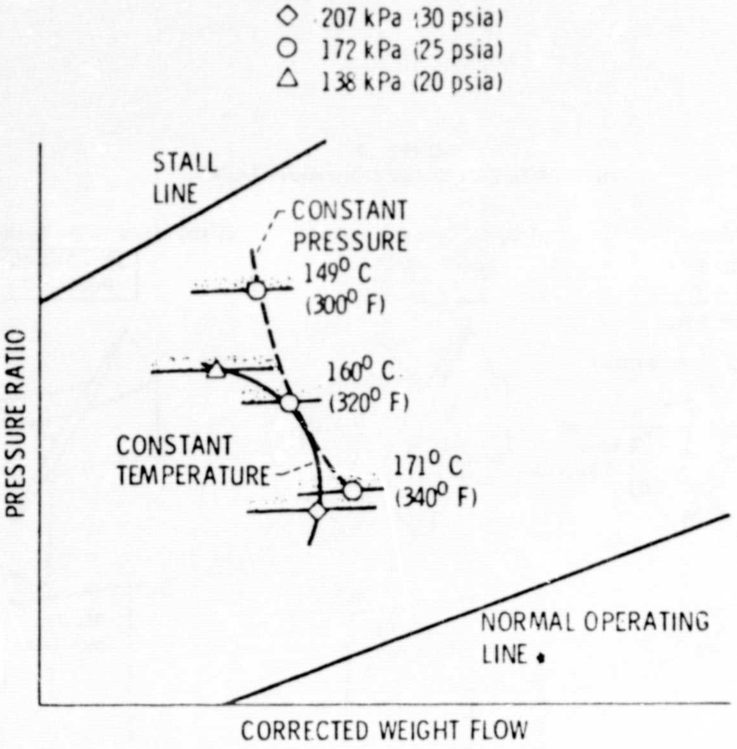


Figure 8. Fan Performance Map Showing Inlet Pressure and Temperature Effect on Turbofan Stall Flutter Boundary

FIGURE 9
VIBRATORY AMPLITUDE DISTRIBUTION AT FLUTTER FREQUENCY

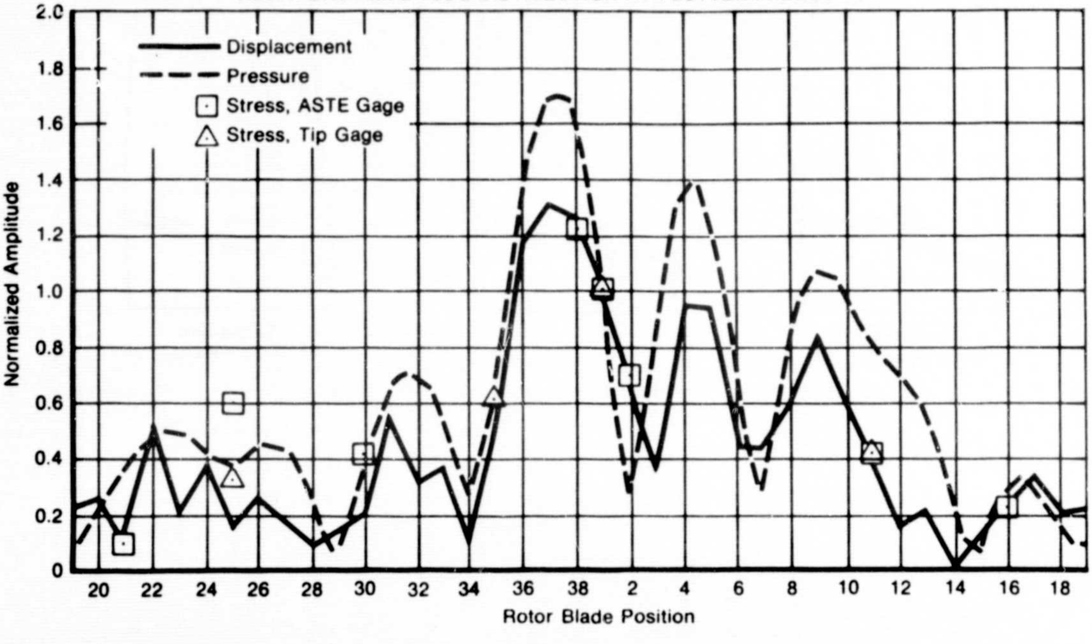


FIGURE 10
1ST-STAGE FAN BLADE CONFIGURATIONS

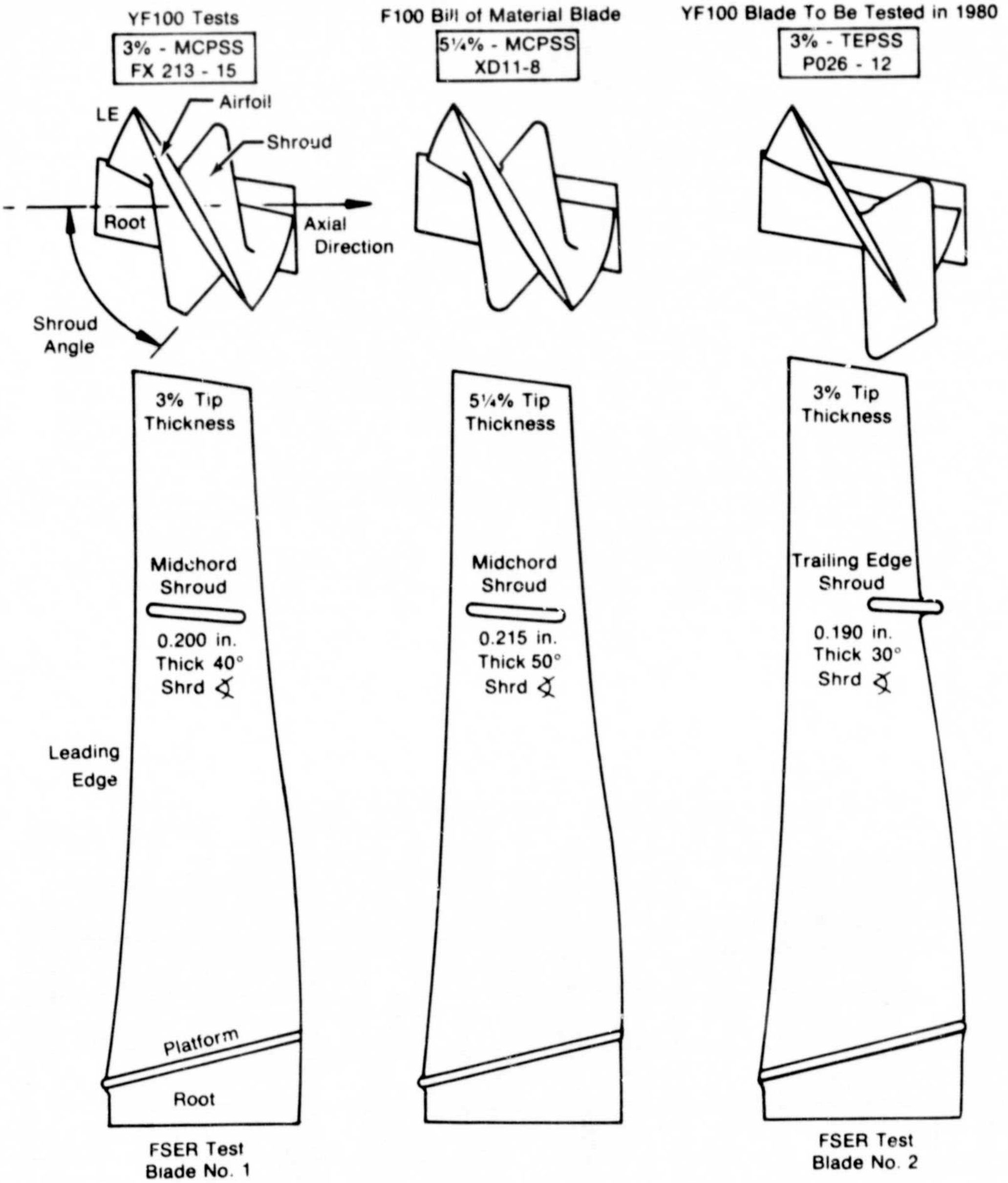
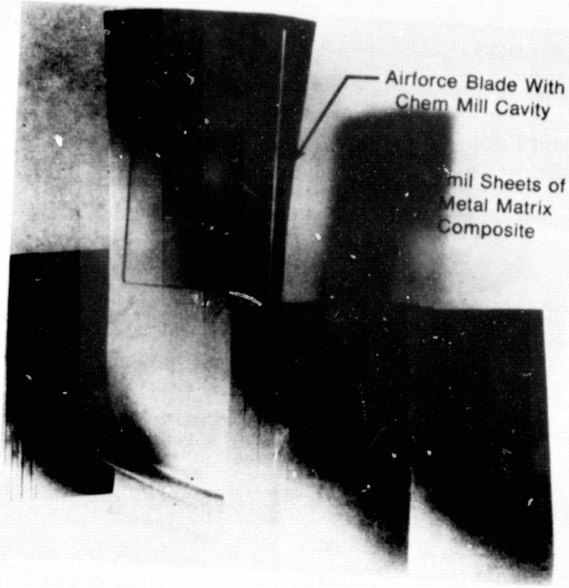


FIGURE 11
COMPOSITE INLAY FAN BLADE
Full Size Blade Ply Elements and Cover Skins



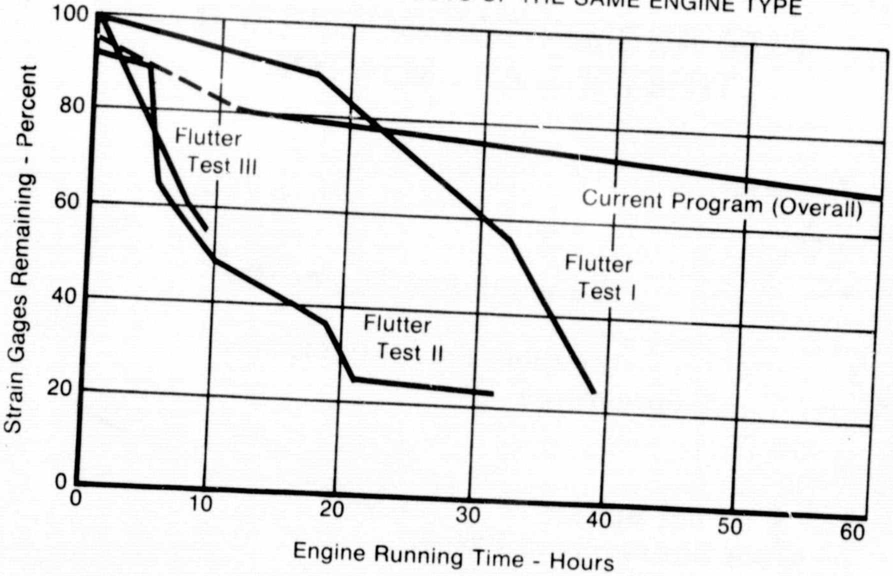

STRAIN GAGE SYSTEM FAILURE RATES FOR THE STRAIN GAGE PROGRAM AND PREVIOUS FLUTTER TESTS OF THE SAME ENGINE TYPE

Figure 12.

DUCTED FLAMEHOLDER MODEL AT COLD INLET TEMPERATURES

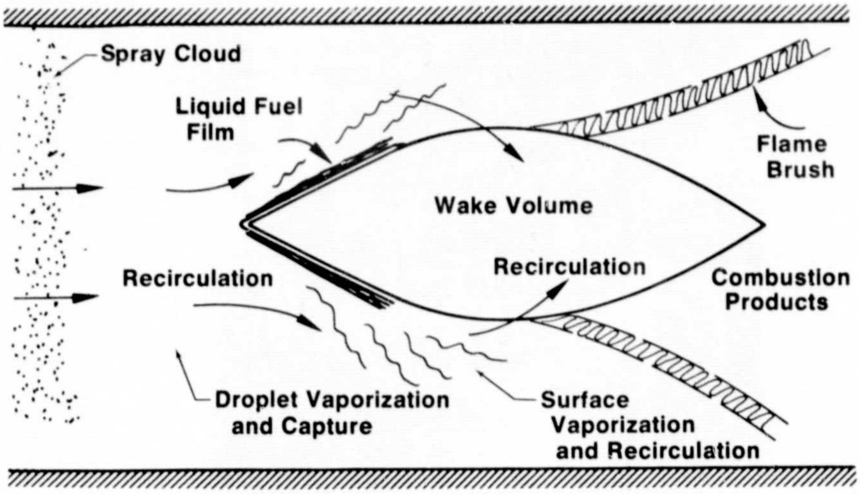


Figure 13.

F100 AUGMENTOR COMPARED TO SWIRL AUGMENTOR

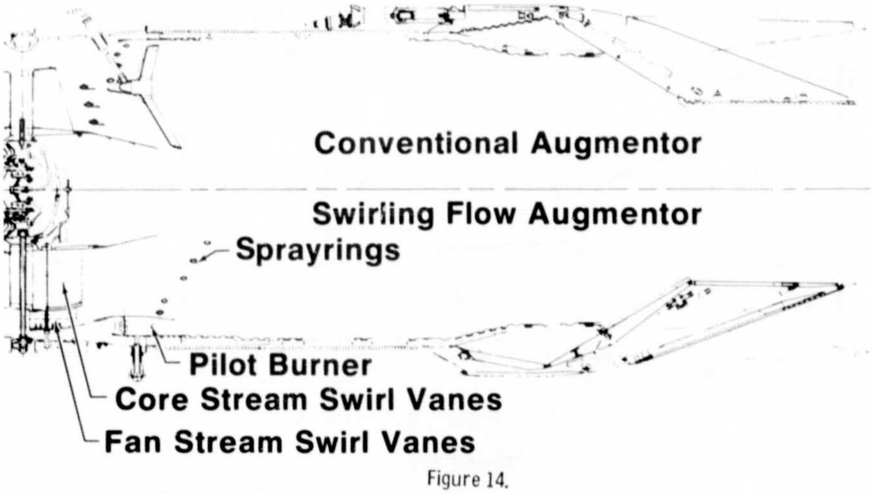


Figure 14.

Full Swirl Augmentor Compared
to F100 Conventional Augmentor

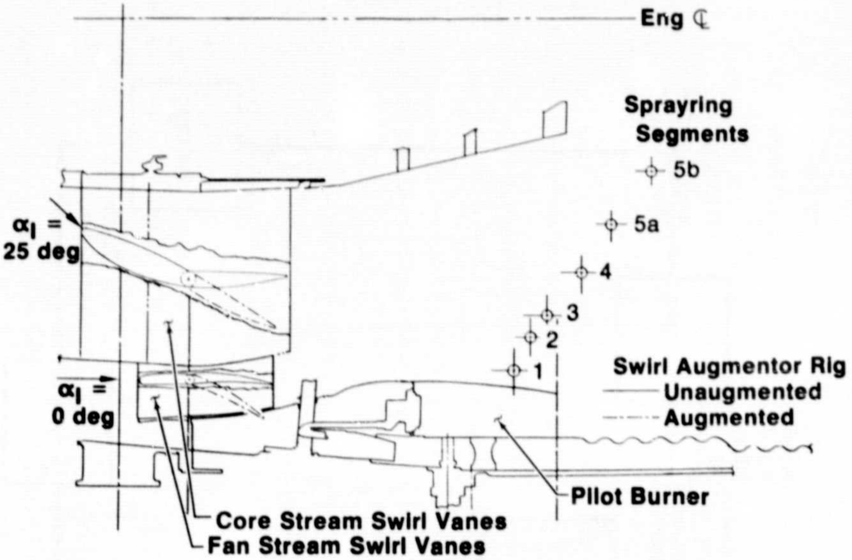


Figure 15(a).

F100 Partial Swirl Augmentor
Configuration Compared to F100(3) Configuration

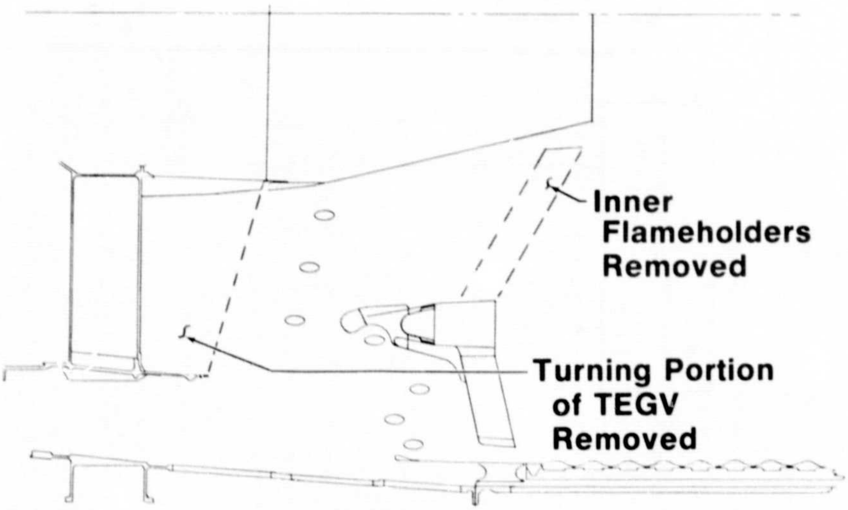
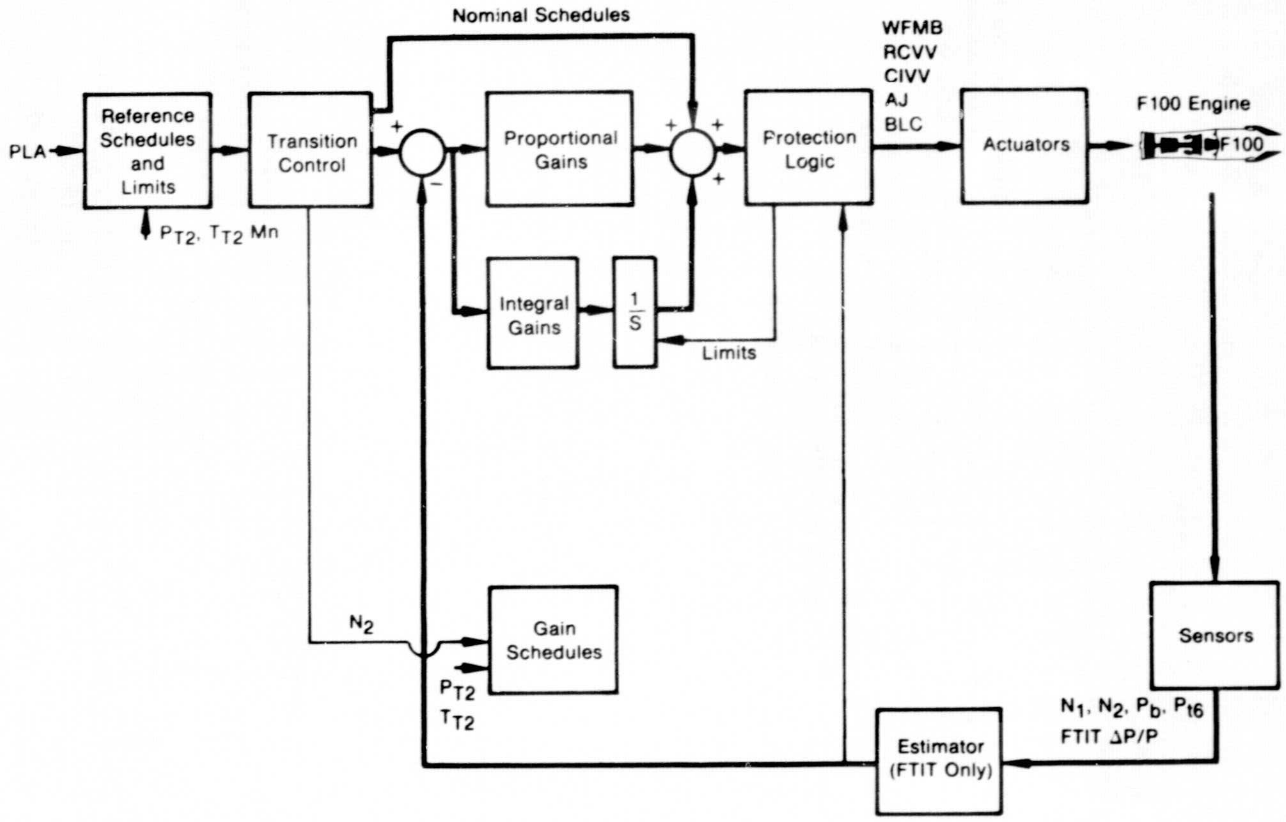
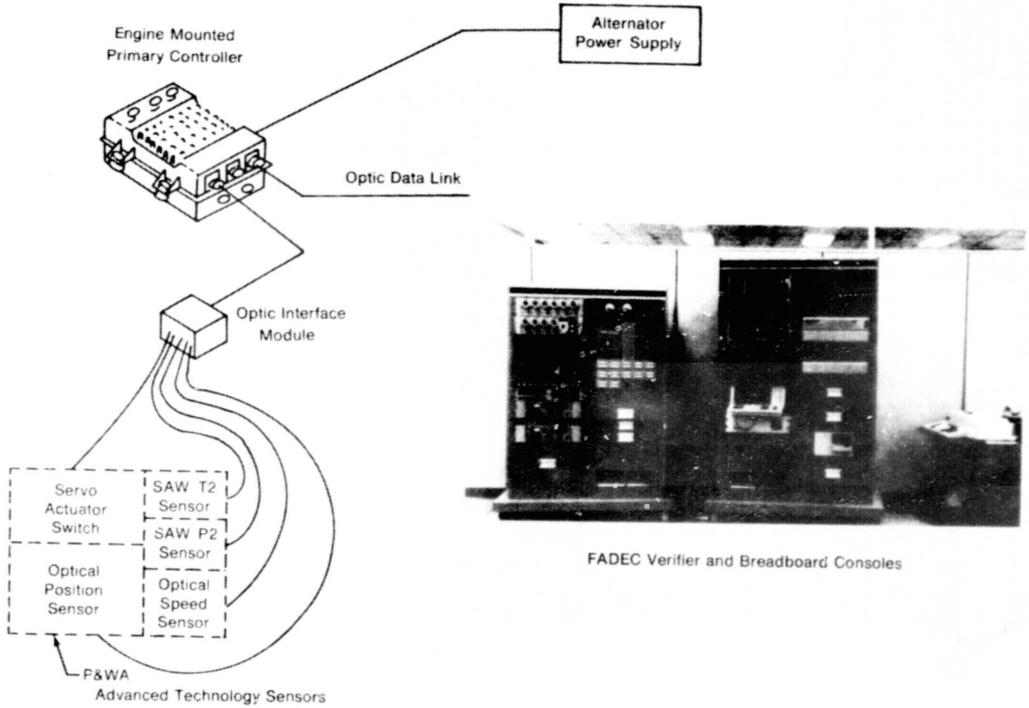


Figure 15(b).

FIGURE 16
F100 MULTIVARIABLE CONTROL ALGORITHM





FADEC Verifier and Breadboard Consoles

Figure 17. FADEC Demonstrator System Components